Study on a cold-cathode H⁻ PIG-type ion source

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Abstract A cold-cathode Penning Ion Gauge (PIG) type ion source as the internal ion source of an 11 MeV cyclotron is designed and tested at Institute of Fluid Physics. The design considerations and some testings are presented. Experimental results of Balmer-line-Emission show that the discharge characteristic, which is mainly determined by gas-flow rate, is not very sensitive to arc current and magnetic field in the operation ranges of the cyclotron. The arc power decreases and ascends while the gas-flow rate goes up from 0.5 SCCM to 20 SCCM. By improving the sealing design and reducing the machine tolerance of the source, the minimum power consumption reduces from 9 SCCM to 4 SCCM, thus having better energy efficiency and benefiting for the pumping system. Preliminary DC extractions show that H^- microampere current ranges from several tens to hundreds under different operation conditions. Some problems during the experiments and future plan are discussed in the end.

Key words PIG-type ion source, Cyclotron, Balmer-line-Emission, H^- current

1 Introduction

A compact cyclotron, which is being built and tested at Institute of Fluid Physics (IFP), is designed to accelerate H^- to 11 MeV, and H^+ for production of short life-time medical isotopes is expelled out by stripping two electrons of H^- using a carbon foil. This beam-extraction way has very high efficiency and compact size. It is necessary for the cyclotron to use H^- source, and a radially inserted internal H^- source is required because of beam dynamics in the central region and compact design. The PIG-type ion source is a good candidate due to its compact size, low cost, low gas flow, sufficient long life-time, no extra contamination to the cavity of cyclotron, and the perfect source to work under high magnetic field[1–17]. Here, the preliminary works on the source design, testing on a test-stand and the cyclotron are presented.

2 Design outline of the source

The source height is less than 53 mm; and its width, less than 45 mm, as shown in Fig.1. The cathode and anti-cathode are designed as a symmetric structure while their power feedings are separated, that is, the discharge parameters of the two cathodes could be different. Water cooling for the source is due to its high power consumption.

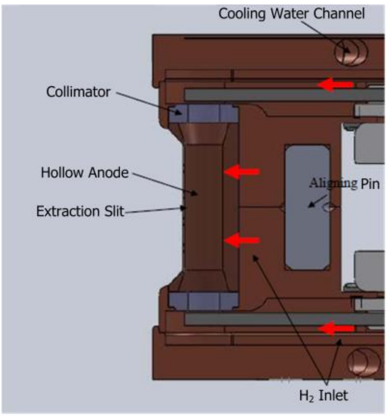

Fig.1 Schematic cutaway view of the head of the ion source.

The water channel is imbedded inside the top / bottom covers. This design has smaller size and better efficiency than that of jointing copper pipes on the cover surfaces. The anode is made of copper alloy with varying inner radius. The extraction slit is 6

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mm×0.4 mm with wall thickness of 0.13–0.16 mm. Two kinds of gas feeding ways are designed. One is that the gas inlets near the extraction slit benefit for the H^- yield but increase gas loading, and the other is that the inlets from the farthest point to the slit require that H_2 gas pass through the hot cathode pole firstly and pre-warmed, thus reducing gas loading. But the comparing experiments have not been conducted yet.

3 Experimental

The test-stand was used to most testing experiments, and simulated the environment inside the cyclotron before it is available. Recently, some experiments on the cyclotron have just finished the high frequency power feeding test.

The test-stand is mainly composted by a dipole magnet and a vacuum cavity in its gap. To save cost and time, an old remodeled electro-magnet could provide 0.7-T maximum magnetic field, almost half of the real field was inside the cyclotron. Since the electron gyro radius in the source in the field of more than 0.1 T is μm level, which is smaller than the source size, the difference of the magnetic field magnitude between the test-stand and the cyclotron could not bring much effect on the source discharge.

Diagnostics on the source emission spectrum and the ion extraction by the way of DC voltage have been carried out by the test-stand, as shown in Fig.2. When exploring the spectrum, the slit will face the quartz window directly without the extractor and collector inside the cavity.

After the cyclotron magnetic field calibration and the radio frequency power were fed into the cavity, the installed source was used to carry out beam tuning. The work field is 1.2 T; and the radio frequency, 72 MHz; and vacuum, 10^{-4} Pa. The designed amplitude of extracting voltage is 37 kV while the real voltage could reach to 45 kV.

4 Experimental results and analysis

The H^- source works at the status of arc discharging. This work status is mainly determined by its structure, electrode materials, and three external conditions including power supply, magnetic field and H_2 feeding. Studying the affect of these parameters on the source discharge characteristics helps to physically comprehend and optimize the source.

4.1 Effect of gas flow on discharge

Balmer lines H_α, H_β and H_γ are recorded by a PI (Princeton Instruments) SP2756A whose resolution is about 0.06 nm in the range 200–1050 nm. The intensity of the emitted light should be proportional to the excited particles[18–20]. When keeping the 1.34-A arc current, and 0.46-T magnetic field unchanged, the emission intensity of the ion source vs. hydrogen flow rate is recorded, as shown in Fig.3.

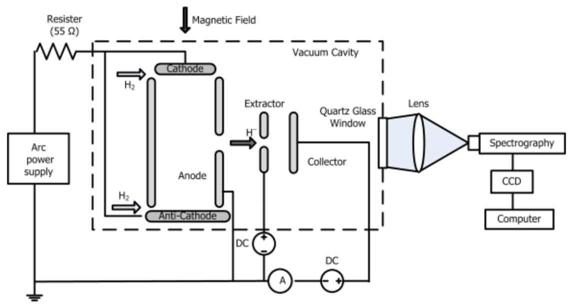

Fig.2 Experimental schematic of the ion source on the test-stand.

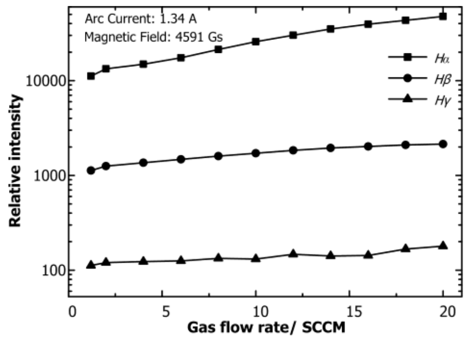

Fig.3 Relative intensity of line emission versus gas flow rate.

The line emission intensity increases with the gas flow rate. In principle, the two effects happen simultaneously. When the electron collision frequency with neutral increases, the amount of the excited atoms is enlarged, emitting more lights. When the electron free path is short, the adverse effect on kinetic energy accrues to electrons, reducing the cross-section of excitation or ionization process. When the gas flow rate increases, the two effects compete with each other, and may result in a peak value of the emission intensity corresponding to the maximum excited atoms. Experimental data do not show this maximum point in the H_2 flow range from 0–20 SCCM (cubic

centimetres per minute at standard temperature and pressure), but there is the minimum source power consumption. In Fig.4, as the gas flow rises, the power consumption rises after decreasing to minimum point. By improving the source sealing design and reducing machine tolerance, the minimum power consumption is reduced from 9 SCCM to 4 SCCM, the higher power efficiency and the better vacuum level. There is still room for further reducing the minimum power consumption in our design.

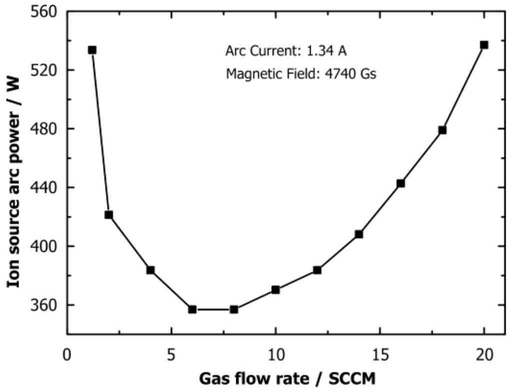

Fig.4 Arc power with respect to the gas flow rate.

4.2 Effects of magnetic field on discharge

Generally, penning source works in a moderate magnetic field of several hundred Gauss. Here, the negative hydrogen penning source works in a stronger magnetic field. The electron gyro radius is smaller than the source size as shown in Fig.5, this proves that the discharge state almost keeps stable when magnetic field varies between 0.3–0.7 T. Also, the source discharge state does not change much when moving from the test-stand to the cyclotron, indicating that the results in the cyclotron could be reliably deduced from most of test-stand experiments.

A phenomenon should be noticed that magnetic field does have some effects on H^- extraction in the tested range. More detailed work is planned for the next study.

4.3 *V-I* characteristic of the ion source

In order to get enough H^-, the H^- source works at arc discharge state of several amperes while most penning sources work at glow discharge state[21]. The *V–I* curve of the source is measured by the cyclotron using 1 SCCM H_2 feeding rate and 1.2-T field. The curve shows (Fig.6) the source could work at any point by adjusting the power source current. During studying the *V–I* characteristic, the power source has been amended several times for better load-match effect. The process of igniting the arc is controllable.

Further, how to monitor erosion of the cathodes and prolong their lives will also be studied except the *V–I* feather.

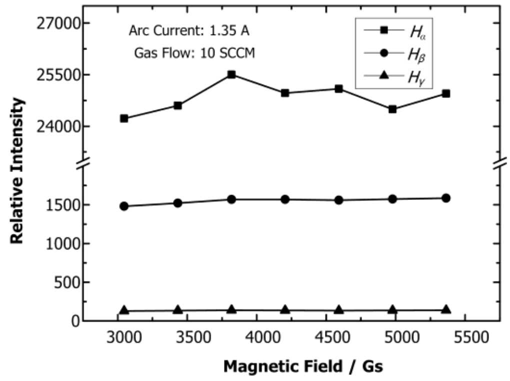

Fig.5 Relative intensity of the emission spectrum with respect to the magnetic field.

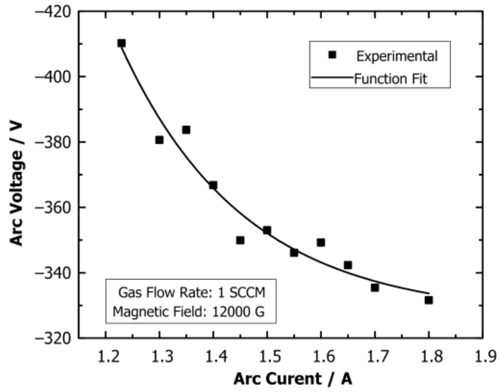

Fig.6 Arc voltage of ion source with respect to the arc current.

4.4 Preliminary ion extraction experiments

The extraction experiments of H^- have been carried out on the test stand and the cyclotron[22]. On the test stand, it is found that the applied DC voltage between the source and the extractor could reach 40 kV when the source does not work. But as soon as the source discharges either in glow or arc state, the DC voltage could not exceed 2 kV. Above the value, the corona on the extractor will occur and the collected negative charge signal increases to several mA quickly. Most part of the signal is contributed by electrons. The value of H^- is around 200 μA extracted by the voltage.

On the cyclotron, the extraction voltage of the frequency field could reach 40 kV. Over 80-μA peak

current of 11 MeV H^- has been gotten at the target zone of the cyclotron. The design goal is 50 μA. Still, many efforts should be conducted to increase the average yield of H^- and prolong its life and operation stability in our next stage. Over 160-μA proton peak current at the target is obtained by inverting the polarity and decreasing the magnetic field slightly, thus verifying that the physical design of the cyclotron is correct.

5 Discussion

The features of negative hydrogen penning source are preliminarily studied, and its prototype has already met the basic engineering requirements of cyclotron, such as size constraints, heat dissipation, gas load and adjustable location. The achieved 11-MeV H^- and H^+ proves that the physical design of the cyclotron of IFP is correct. The yield of H^- and its life are still lower than that is expected. Due to limitations of space and experimental time, the cyclotron test-stand is more suitable to study the source physics. Now, the biggest problem is that the extraction DC voltage could not be adjusted over 2 kV. This is likely that the charges carried out by H_2 gas flow reduced the insulation level of vacuum cavity greatly. Some trial measurements failed to increase the voltage level. We plan to adopt pulsed voltage to the extracted ions together. Further, the comprehension for the physical processes inside the chamber should be considered carefully. The H^- yield is enhanced at the low cost.

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